AKARI Infrared Imaging of Reflection Nebulae IC 4954 and IC 4955

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Abstract

We present the observations of the reflection nebulae IC 4954 and IC 4955 region with the Infrared Camera and the Far-Infrared Surveyor (FIS) on board the infrared astronomical satellite AKARI during its performance verification phase. We obtained 7 band images from 7 to 160 μm with higher spatial resolution and higher sensitivities than previous observations. The spatial variation in the mid-infrared color suggests that the star-formation in IC 4954/4955 is progressing from south-west to north-east. The FIS 4-band data from 65 μm to 160 μm allow us to correctly estimate the total infrared luminosity from the region, which is about one sixth of the energy emitted from the existing stellar sources. Five candidates for young stellar objects have been detected as point sources for the first time in the 11 μm image and it is suggested that that current star-formation has been triggered by previous star-formation activities. A wide area map of the size of about 1° around the IC 4954/4955 region was created from the AKARI mid-infrared All-Sky Survey data. Together with the H I 21 cm data, it suggests a large hollow structure of a degree scale, on whose edge the IC 4954/4955 region has been created, indicating star formation over three generations in largely different spatial scales.

Key words: infrared: ISM — ISM: individual (IC 4954, IC 4955) — open clusters: individual (Roslund 4) — stars: star formation

1. Introduction

The reflection nebulae IC 4954 and IC 4955 are located in the Vulpecula constellation on the galactic plane around $(l, b) = (66°, 96°, -1°26′)$. These nebulae are associated with the young open cluster Roslund 4 (Roslund 1960). The heliocentric distance and the age of this cluster were estimated based on the analysis of isochrones as 10 Myr and 2.9 kpc by Racine (1996), 4 Myr and 2 kpc by Phelps (2003) (hereafter P03), and 15 Myr and 2 kpc by Delgado et al. (2004) (hereafter D04). These studies suggest the presence of stars of a relatively wide age range and on-going star-formation in the IC 4954/4955 region. In this paper we assume the distance to be 2 kpc. P03 and D04 also detected three active regions in [S II] images and some of them are classified as Herbig–Haro objects. The Hα, [N II], and [S II] emission lines from the cluster members are detected in optical spectroscopic observations (D04). This region is an interesting place for studying the of star-formation process because of the co-existence of both young and relatively old populations (P03; D04). Except for the dedicated observation of D04, the parallax, radial velocity, proper motions, and spectral type of the cluster members (or clues for the identification of the members) are largely unavailable in existing catalogs because of its far heliocentric distance.

$^{12}$CO observations show that at least one cloud of $10^5 M_\odot$ is associated with this region (Leisawitz et al. 1989). In the infrared, these nebulae are observed in the IRAS and MSX galactic surveys. The IRAS Point Source Catalog (PSC) has entries of three point sources in this region, whereas the MSX map shows distinguished structures in four mid-infrared bands of A (8.28 μm), C (11.2 μm), D (14.3 μm), and E (21.34 μm). However, the poor spatial resolution of IRAS and the insufficient sensitivity of the MSX prevent us from making a detailed analysis of this interesting region in the infrared. This region is not included in the Galactic Legacy Infrared Mid-Plane Survey Extraordinaire with Spitzer (GLIMPSE; Benjamin et al. 2003).

AKARI is the first Japanese infrared astronomical satellite dedicated for infrared astronomy (Murakami et al. 2007). It has...
two scientific instruments: the Infrared Camera (IRC; Onaka et al. 2007b) that covers near- and mid-infrared wavelengths of 2–26 μm, and the Far-Infrared Surveyor (FIS; Kawada et al. 2007) that covers the far-infrared spectral range of 50–200 μm. The performances of both instruments were confirmed by observations during the performance verification (PV) phase from 2006 April 24 to May 8. The present paper reports on the results of observations of the IC 4954/4955 region with both IRC and FIS taken mainly during the PV phase.

The observations and data reduction are described in section 2. The observational results are shown in section 3. The nature and the origin of the Roslund 4 region are discussed in section 4. Finally, we summarize the results in section 5.

2. Observations and Data Reductions

AKARI seven-band images were taken by two scientific instruments with three kinds of operation mode. The observational parameters are summarized in Table 1.

<table>
<thead>
<tr>
<th>( \lambda_{\text{ref}} ) (μm)</th>
<th>( \Delta \lambda ) (μm)</th>
<th>FWHM (”)</th>
<th>Pix scale (” × ”)</th>
<th>Scan speed (” s(^{-1}))</th>
<th>Instrument</th>
<th>Filter</th>
<th>AOT</th>
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<td>S9W</td>
<td>ASS</td>
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<td>S11</td>
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<td>39</td>
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<td>WIDE-S</td>
<td>FIS01</td>
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<tr>
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<td>58</td>
<td>44.2 × 44.2</td>
<td>15</td>
<td>FIS</td>
<td>WIDE-L</td>
<td>FIS01</td>
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<td>61</td>
<td>44.2 × 44.2</td>
<td>15</td>
<td>FIS</td>
<td>N160</td>
<td>FIS01</td>
</tr>
</tbody>
</table>

2.1. IRC All-Sky Survey (9 and 18 μm)

The S9W (9 μm) and L18W (18 μm) data of the IC 4954/4955 region were taken as part of the All-Sky Survey observations. Both data were taken simultaneously with different channels of the IRC, mid-infrared short (MIR-S), and mid-infrared long (MIR-L), which observe sky positions separated by about 20’ in the cross-scan direction (Onaka et al. 2007b). In the All-Sky Survey, the IRC is operated in the scan mode (Ishihara et al. 2006a), in which the data of only two rows in the detector arrays are taken with a cross-scan width of about 10’. The scan speed is about 215” s\(^{-1}\). The output signals of every four adjacent pixels are binned together to reduce the data down-link rate, and the virtual pixel scale is 9.36 × 9.36” in the survey mode. A second confirmation is enabled by independent data sets taken by the two separated rows, which allow one to efficiently reject high-energy ionization particle events, and largely improves the reliability of source detection. Finer spatial information as well as improved sensitivity can be expected in the data-reduction process because two rows are sampled and binned in an interlaced manner and the observed strip is shifted by 4’ in adjacent scan paths with a given region being observed more than twice on average. The reset interval is set as 13.5 s, which corresponds to 306 samplings or 48.9 in the scanning direction. The length of a reset in the All-Sky Survey is set as 2.2 ms (hereafter long reset). The IC 4954/4955 region was observed during 2006 May 1–8 in the PV phase with a descending path of \( \frac{d\beta}{dt} < 0 \) and 2006 November 1–8 with an ascending path of \( \frac{d\beta}{dt} > 0 \), where β is the ecliptic latitude. Both data were averaged with the median in the present analysis. The difference between the two data sets is less than 10% in the sky brightness.

Fragments of the data sets covering IC 4954/4955 are retrieved from the IRC All-Sky Survey database and reduced automatically by pipeline software to create a map (D. Ishihara et al. 2007, in preparation). The pipeline process includes a linearity correction, a flat correction, a reset anomaly correction (see below), source extraction, rejection of high-energy particle events by the second confirmation, a position determination using identified objects, coaddition of the images obtained by the two rows, and map construction.

The flux calibrations of point sources in the All-Sky Survey data are carried out based on a large number of detections of hundreds of stars in the standard star networks (Cohen et al. 1999, 2003; Ishihara et al. 2006b). The flux accuracy is estimated as \( \sim 7\% \) for the S9W band and \( \sim 15\% \) for the L18W band for point sources at the present calibration stage. The detection limits (5σ) for point sources were estimated as 50 mJy for the S9W band and 120 mJy for the L18W band. The calibration for diffuse emission is on-going and a relative error of 30% is assigned at present.

The positions of the detected objects were first estimated based on the data of the gyroscopes and the star trackers on board, and were then refined by using the positions of bright \((K < 8\) mag\)) 2MASS PSC sources. The position accuracy is estimated to be 5” at present.

2.2. IRC Slow Scan (11 μm)

The S11 (11 μm) band image was obtained during the PV phase with the IRC slow-scan mode of the Astronomical Observation Template (AOT) IRC51. IRC51 is a set of round-trip scans designed for mapping of a small area of up to \( \sim 10’ \times 120’ \) in about 15 min of a pointed observation (Murakami et al. 2007; Onaka et al. 2007b). A higher sensitivity than in the All-Sky Survey and a wider sky coverage than in imaging observations can be achieved in this observation mode. It also one allows to observe very bright sources, such as IC 4954/4955, which will be saturated in the imaging observation. The scan speed was set as 30”s\(^{-1}\) and the S11 filter was selected. The observation of IC 4954/4955 was carried out on 2006 May 1.
The focal plane arrays were operated in the same scan mode as in the All-Sky Survey observations, except that data binning was not made, and the full spatial information was obtained in the cross-scan direction. A confirmation of source detection was made by round-trip scans. The grid size of slow-scan observations was set as 1″32 × 2″34. It was determined by the physical pixel size in the cross-scan direction (2″34), and by the sampling rate and the scan speed in the scanning direction (1″32). It oversampled the image size of the imaging mode at 11 μm (~ 4″8; Onaka et al. 2007b). The time spent for a reset was shortened to 68 μs (short reset). The charge integration curve shows an anomalous behavior immediately after a reset (reset anomaly). The magnitude of this effect depends on the time spent for a reset. We confirm that the short reset significantly improves the reset anomaly effect. Gaps in the observed area due to the reset was thus reduced thanks to a combination of the slower scan speed and the short reset. The reset period was also shortened to 2.24 s because the gap due to the reset could be ignored. Consequently, the effect of saturation was also reduced. There is a drift in the offset level owing to a temperature drift (Ishihara et al. 2003). It was corrected by referring to the signal level during the reset. The signal during the reset corresponds to the output with the input blocked, and thus indicates the offset level of the preamplifier. The detection limit was determined by the read-out noise of the detector, rather than the zodiacal background fluctuation because of the short sampling time.

The data reduction largely follows that for the All-Sky Survey, except for a few parameters adjusted for the finer pixels, such as flat correction, and a custom-designed map reconstruction module is developed. At first the data taken in a single scan are arranged into a 10′ × 60′ strip image by assuming that the sampling rate and the scan speed of the satellite are constant. Individual sets of images obtained by two separated rows are aligned with each other and coadded into a combined image. The position reconstruction of the map is made based on the association with detected 2MASS sources as in the All-Sky Survey data. The positional accuracy of the data is estimated to be 5″ at present.

An in-flight calibration of the IRC was carried out for all of the imaging filters in pointed imaging observations based on observations of the standard star networks (Onaka et al. 2007b). For the all-sky observations and slow-scan observations, however, most observations were made only with the S9W and L18W bands. The flux calibration for the S11 (11 μm) band image in the slow-scan observations was performed in an indirect way because no observations of standard stars have been made in the same scan speed with the same filter. First, the calibration for the S9W in the slow-scan mode with the scan speed of 30″ s⁻¹ was made by a comparison of the fluxes derived from slow-scan observations with those from the All-Sky Survey for the same stars. Then, the calibration for the S11 band with the scan speed of 30″ s⁻¹ is estimated by assuming the relative calibration between the S9W and S11 bands in pointed imaging observations. Taking account of the uncertainties in the indirect calibration, we set a conservative uncertainty of 30% in the S11 data at present.

2.3. FIS Slow Scan (65, 90, 140, 160 μm Band)

FIS observations of IC 4954/4955 were executed with the N60 (65 μm), WIDE-S (90 μm), WIDE-L (140 μm), and N160 (160 μm) bands in the 2-round-trip slow-scan mode (FIS01) with a scan speed of 15″ s⁻¹ on 2006 May 3. The four-band data were taken simultaneously with correlated double sampling (CDS) in about 15 min of a pointed observation. Details of the observation scheme and the data reduction of the FIS slow scan data are described in Kaneda et al. (2007) and Suzuki et al. (2007). At present, the systematic flux calibration errors for the CDS mode are estimated to be 30, 40, 50, and 50% for N60, WIDE-S (90 μm), WIDE-L (140 μm), and N160, respectively. The relative position accuracy among the FIS bands is better than 1″, because they were taken simultaneously, but the absolute accuracy is estimated to be about 1″. Thus, all of the FIS images are aligned relative to the IRC images in the equatorial coordinates. Since the IRC data were taken at a different epoch from that of FIS, the relative position accuracy is estimated to be about 30″ at present.

3. Results

3.1. Infrared Images of IC 4954 and IC 4955

The images of IC 4954/4955 in the AKARI S9W, S11, L18W, N60, WIDE-S (90 μm), WIDE-L (140 μm), and N160 bands are shown in figure 1. The northern nebula in the image is IC 4955 (enclosed by the green line in figure 1a) and the southern nebula is IC 4954 (enclosed by the red line). The AKARI images reveal several distinct characteristics of the nebulae.

The AKARI S9W map by the All-Sky Survey was created with a grid size of 1″56 × 1″56 from a virtual pixel size of 9″36 × 9″36. It is in good agreement with the MSX A-band (8.28 μm) image. The AKARI S9W band has a better spatial resolution and a relative spectral response similar to that of the MSX A-band, except for inclusion of a 11.2 μm unidentified infrared (UIR) band (Onaka et al. 2007b). Three IRAS point sources exist in this region, as indicated in the S9W image. The location of IRAS 20026+2906 does not match with the bright spot in the S9W images (source F in figure 1b), probably due to the complicated background structures in this region.

The S11 image has the finest resolution and the deepest sensitivity among the seven bands owing to its observing mode. Point-like objects are clearly resolved and denoted by A–L (for details see subsection 3.2). Distinct extended structures are denoted by a–h. The northern nebula IC 4955 is spatially resolved into two condensations (a and d) and two arc-like structures (b and c). The two arcs may overlap with each other on the line-of-sight. Arc-like structures are also found in IC 4954 (e and f). All of the arcs point toward the north-east of the nebulae and extend over the outer edge of the nebula emission in the optical image.

The AKARI L18W image has a higher signal-to-noise ratio and higher spatial resolution than the MSX E-band (21.2 μm) image. Point-like objects (g–n) are clearly seen in figure 1c. The spatial distribution of the 18 μm emission seems to be significantly different from that of the S9W or S11 emission. See subsection 4.1 for a discussion on the morphologies of the
Fig. 1. IC 4954/4955 images by AKARI observations: (a) S9W (9 μm), (b) S11 (11 μm), (c) L18W (18 μm), (d) N60 (65 μm), (e) WIDE-S (90 μm), (f) WIDE-L (140 μm), and (g) N160 (160 μm) bands in the equatorial coordinates (J2000.0). The integrated areas in the photometry for each nebula are shown on the S9W image (a) with the red line for IC 4954 and the green line for IC 4955. Three IRAS point sources are also indicated by the plusses. The symbols a–f in the S11 (b) and g–n in the L18W (c) indicate distinct structures in the images. The symbols A–L show point-like sources in the S11 image (b).
faint arc-like structure toward the south-east is also detected. The WIDE-L band fluxes are also very low compared to the S11 flux (see table 3), suggesting that the MSX flux includes contributions from the surrounding diffuse emission, since the source is located in an extended emission region. In the vicinity of source K, there are two MSX sources (G066.9646—01.2783 and G066.9609—01.2776), whose C band flux (12.13 μm) is much larger than the S11 flux (see table 3), suggesting that the MSX flux includes contributions from the surrounding diffuse emission, since the source is located in an extended emission region. In the vicinity of source K, there are two MSX sources (G066.9646—01.2783 and G066.9609—01.2776), whose C band fluxes are also very low (see table 3). G066.9646—01.2783 seems to correspond to source K in position, and G066.9609—01.2776 seems to be located close to another optically bright source, 2MASS 20045331+2911469, around which the S11 image does not show the source.

### Table 2. Photometric results of IC 4954 and IC 4955.

<table>
<thead>
<tr>
<th>Object</th>
<th>S9W 9 μm</th>
<th>S11 11 μm</th>
<th>L18W 18 μm</th>
<th>N60 65 μm</th>
<th>WIDE-S 90 μm</th>
<th>WIDE-L 140 μm</th>
<th>N160 160 μm</th>
</tr>
</thead>
<tbody>
<tr>
<td>IC 4954</td>
<td>62.1 ± 18.7</td>
<td>61.1 ± 18.3</td>
<td>56.2 ± 16.9</td>
<td>790 ± 240</td>
<td>860 ± 260</td>
<td>2500 ± 1000</td>
<td>1890 ± 570</td>
</tr>
<tr>
<td>IC 4955</td>
<td>33.6 ± 10.1</td>
<td>33.4 ± 10.2</td>
<td>31.2 ± 9.36</td>
<td>330 ± 100</td>
<td>340 ± 100</td>
<td>1700 ± 680</td>
<td>850 ± 260</td>
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**MSX data**

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<th>14.65 μm</th>
<th>21.34 μm</th>
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</thead>
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<td>IC 4954</td>
<td>55.15 ± 0.26</td>
<td>75.15 ± 2.25</td>
<td>32.29 ± 1.29</td>
<td>66.84 ± 4.01</td>
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<td>IC 4955</td>
<td>28.86 ± 1.44</td>
<td>40.25 ± 1.21</td>
<td>16.10 ± 0.64</td>
<td>36.21 ± 2.17</td>
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**IRAS PSC sources**

<table>
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<th>IRAS name</th>
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<th>60 μm</th>
<th>100 μm</th>
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<td>20026+2906</td>
<td>2.741 ± 0.66</td>
<td>&lt; 0.25</td>
<td>&lt; 3.186</td>
<td>&lt; 66.76</td>
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<tr>
<td>20027+2905</td>
<td>3.356 ± 0.30</td>
<td>14.06 ± 0.70</td>
<td>&lt; 540.3</td>
<td>&lt; 50.71</td>
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<tr>
<td>20028+2903</td>
<td>20.26 ± 0.81</td>
<td>47.29 ± 1.89</td>
<td>540.3 ± 48.6</td>
<td>1177 ± 129</td>
</tr>
</tbody>
</table>

* Units are in Jy.

**S9W and L18W images.**

The AKARI N60 (65 μm) and WIDE-S (90 μm) images surpass the IRAS 60 or 100 μm images. The two nebulae are spatially resolved in this wavelength range for the first time. A faint arc-like structure toward the south-east is also detected. The WIDE-L (140 μm) and N160 (160 μm) data are unique to AKARI. These two bands make significant constraints on the dust emission (figure 2) for an estimate of the total infrared luminosity (subsection 4.1).

The total fluxes from IC 4954 and IC 4955 were derived from the integrated signals in the regions enclosed by the red and green lines in figure 1a and the sky background was estimated from the surrounding region and subtracted. The results of IC 4954 and IC 4955 are summarized in table 2 and their spectral energy distributions (SEDs) are plotted in figure 2. The uncertainties in table 2 include systematic errors. The MSX image data at bands A (8.28 μm), C (12.13 μm), D (14.65 μm), and E (21.3 μm) were also integrated over the same regions, and the sky background was subtracted similarly. The results are plotted in figure 2. Except for the band D data, the IRC data are in fair agreement with the MSX data, taking account of the uncertainties and the differences in the band profiles. The band D data are fainter even compared to other MSX band data for both nebulae.

In figure 2 are also plotted the IRAS PSC data. It is not possible to estimate the fluxes for IC 4954 and IC 4955 directly from the IRAS data, since the sources are not clearly resolved. In the figure, the fluxes of IRAS 20028+2903 are plotted as IC 4954, whereas the sum of the fluxes of IRAS0026+2906 and IRAS2007+2905 are indicated as IC 4955. Except for the 60 μm data, the IRAS fluxes are lower than the AKARI/IRC and FIS fluxes and the agreement is not very good. The difference can be attributed to the fact that the IRAS data do not include the diffuse emission correctly in addition to the position mismatch of IRAS 20026+2906.

### 3.2. Newly Detected Point-Like Sources

The fluxes and positions of 12 point-like objects detected in the S11 image (indicated by A–L in figure 1b) are summarized in table 3. They all have corresponding 2MASS sources, as indicated in the table. The SED of each source is plotted in figure 3, including the 2MASS data. There is a MSX source (G066.9971—01.2247) close to source F, whose C band flux (12.13 μm) is much larger than the S11 flux (see table 3), suggesting that the MSX flux includes contributions from the surrounding diffuse emission, since the source is located in an extended emission region. In the vicinity of source K, there are two MSX sources (G066.9646—01.2783 and G066.9609—01.2776), whose C band fluxes are also very large (see table 3). G066.9646—01.2783 seems to correspond to source K in position, and G066.9609—01.2776 seems to be located close to another optically bright source, 2MASS 20045331+2911469, around which the S11 image does not show the source.
Table 3. Point sources detected in the S11 image.

<table>
<thead>
<tr>
<th>ID</th>
<th>RA (J2000.0) (h m s)</th>
<th>Dec (J2000.0) (° ′ ″)</th>
<th>2MASS ID</th>
<th>11 μm flux (mJy)</th>
<th>MSX source</th>
<th>MSX band C flux (Jy)</th>
</tr>
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<td>A</td>
<td>20 04 56</td>
<td>+29 11 17</td>
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<td>B</td>
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<td>+29 11 16</td>
<td>20044653+2911167</td>
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<td>C</td>
<td>20 04 49</td>
<td>+29 11 48</td>
<td>20044974+2911486</td>
<td>55.6±1.2</td>
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<tr>
<td>D</td>
<td>20 04 43</td>
<td>+29 12 49</td>
<td>20044366+2912496</td>
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<td>E</td>
<td>20 04 45</td>
<td>+29 13 39</td>
<td>20044585+2913389</td>
<td>22.3±0.5</td>
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<td>F</td>
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<td>G</td>
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</tr>
<tr>
<td>K</td>
<td>20 04 52</td>
<td>+29 11 43</td>
<td>20045278+2911435</td>
<td>208.5±4.4</td>
<td>G066.9646—01.2783*</td>
<td>5.4393</td>
</tr>
<tr>
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<td>G066.9609—01.2776†</td>
<td>3.6187</td>
</tr>
<tr>
<td>L</td>
<td>20 04 54</td>
<td>+29 12 07</td>
<td>20045478+2912080</td>
<td>14.3±0.3</td>
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</tr>
</tbody>
</table>

* Most probable MSX source that corresponds to K.
† No corresponding point source in the S11 image (see text).

Fig. 3. Spectral energy distribution in the near- to mid-infrared of 12 detected sources in the S11 image (figure 1). The J, H, and K data are taken from the 2MASS catalog.

detect any point source. The large MSX fluxes can also be attributed to diffuse emission around the source. Except for F and K, 10 sources were detected as point sources for the first time in the mid-infrared by the present IRC observations.

4. Discussion

4.1. Infrared Characteristics of IC 4954 and IC 4955

The total infrared luminosity from the nebular region can be estimated from the AKARI observations. The AKARI
Fig. 4. Synthesized color images of IC 4954/4955 in the equatorial coordinates: (Left) Optical three-color image of Blue (blue), Red (green), and IR (red) of the DSS image; (Middle) mid-infrared three-color image made from the S9W (blue), S11 (green), and L18W (red) images taken with the AKARI/IRC. Optically known early-type stars are indicated by the crosses with the spectral types (Delgado et al. 2004; Merrill et al. 1942). The symbols of C, F, J, K, and L in blue show point-like objects in the S11 image, a–f (green) indicate structures seen in the S9W or S11 images, and g–n (yellow) denote structures seen in the L18W image, as depicted in figures 1b and c. Red (H/K > 0.9 and J/H > 0.9) sources selected from the 2MASS catalog are shown by the orange circles. The spectral types of the stars are indicated in white. (Right) Far-infrared three-color image of IC 4954/4955 made from the N60 (blue), WIDE-S (90 μm) (green), and WIDE-L (140 μm) (red) images taken with the AKARI/FIS.

IRC and FIS data (figure 2) were fitted by a three-temperature dust model with the emissivity proportional to $\lambda^{-2}$. The three temperatures were fixed as 20, 40, and 230 K for both nebulae. The fitted models are shown by the solid and dotted lines in figure 2 for IC 4954 and IC 4955, respectively. The total infrared luminosity, $L_{\text{IR}}$, was then calculated by

$$L_{\text{IR}} = \sum_{i=1}^{3} \int C_i B(T_i, \lambda) \lambda^{-2} d\lambda,$$  

where $T_i = 20, 40,$ and 230 K for $i = 1, 2,$ and 3, respectively, and $C_i$ is the fitting constants. We obtained $L_{\text{IR}} = 9.5 \times 10^{3}$ and $4.2 \times 10^{3} L_{\odot}$ for IC 4954 and IC 4955, respectively, the sum of the two nebulae being $1.4 \times 10^{4} L_{\odot}$.

The total stellar luminosity available for dust heating can be estimated by summing up the stellar luminosity $L_{\ast}$ of all the stars located in the region as

$$L_{\text{stellar}} = \sum_{\text{members}} L_{\ast}.$$  

The luminosity of each star is estimated simply based on its spectral type with the assumption that they are on the main sequence (Schmidt-Kaler 1982; Johnson 1996; de Jager et al. 1987). We selected 13 stars that have known spectral types and assigned to members of this region (D04). We also select other 11 stars whose spectral types were estimated to be earlier than B7, based on their color. A total of 24 stars in this region were included in the estimate of $L_{\text{stellar}}$. The spectral type was taken from the spectral classification or estimated from the reddening corrected $U - B$ and $B - V$ in D04. The membership assignment and the UBVRI photometric results (D04) were obtained from WEBDA.\(^1\) The locations of the 24 stars used in the estimation are shown by the crosses in figure 4a. The O8en star reported in Merrill et al. (1942), located south-west of the nebulae (shown in figure 4b) was not included in the estimation, because it seems to be too far from the nebula region. Even if we include this star, the total stellar luminosity will be increased only by 15%, and it will not affect the present conclusion. The total stellar luminosity in this region, thus estimated as $8.3 \times 10^{4} L_{\odot}$. It is about 6-times $L_{\text{IR}}$. Leisawitz and Hauser (1988) have indicated that typically only a small fraction ($\sim 0.2$) of the cluster luminosity is absorbed by dust grains. The present result is in good agreement with their results, suggesting that it is not very likely that there are very luminous stars hidden in dusty environments in this region.

With the dust mass emissivity at 100 μm being 0.6 g cm$^{-2}$ (Hildebrand 1983), the dust mass associated with IC 4954 and IC 4955 was derived to be about 40 and 20 $M_{\odot}$, respectively. The typical size of the nebulae was estimated from the intensity contours of 10% of the peak to be about 1.3, or $2 \times 10^{18}$ cm. Assuming that the gas-to-dust ratio is 100, the average gas density of the infrared emitting medium is estimated to be about $(2-4) \times 10^{3}$ cm$^{-3}$. This is in the range of the density of dense photo-dissociation regions (PDRs), such as the Orion region (Tielens & Hollenbach 1985), indicating that the IC 4954/4955 region is still a young star-forming

\(^1\) (http://obswww.unige.ch/webda).
region, rather than diffuse PDRs, such as the Carina nebula (Mizutani et al. 2004).

Color images of IC 4954/4955 in the optical, mid-infrared, and far-infrared are shown in figure 4. In the mid-infrared, the spatial distribution of the 9 \(\mu\)m emission is similar to that of the 11 \(\mu\)m emission, whereas the difference in the spatial distribution between S9W and L18W images is remarkable. Figure 5 shows the relative spectral response of the S9W, S11, and L18W bands. Also plotted by the thin solid line is an interstellar cirrus spectrum taken with Spitzer/IRS for a reference. The S9W band includes the major UIR bands at 6.2, 7.7, 8.6, and 11.2 \(\mu\)m, except for the 12.7 \(\mu\)m band, and is not affected by continuum emission longer than 12 \(\mu\)m. The S11 band is affected by only part of the UIR 7.7 \(\mu\)m, but includes the UIR 11.2 and 12.7 \(\mu\)m, and the [Ne II] 12.8 \(\mu\)m line emission. In the L18W the UIR 17 \(\mu\)m complex is included and the main contributor is the continuum emission longer than 15 \(\mu\)m. No appreciable difference seen between the S9W and S11 images suggests that the spectrum shape between 6 to 13 \(\mu\)m does not vary significantly in the region, and that the line emissions from ionized species is insignificant compared to the UIR band emission. The difference between S9W and L18W should be related to the variation in the continuum emission longer than 15 \(\mu\)m. The S9W image shows arc-like structures clearly and the L18W image indicates high concentration of the emission in narrow areas. The difference can be seen noticeably in the mid-infrared color image (figure 4b). The emission in L18W is stronger inside the arcs, as indicated by red. Most of the regions highlighted by red color are associated with B type stars, which are supposed to act as heating sources of the region: in the region g, there are a B star and a B9 star; region h is associated with a B2 star and a B7 star; a B type star in region n is suggested to not belong to the member of this region on the basis of the radial velocity (D04), and thus may not be related to this region. The other nearby B5 star must be a heating source of this region. The red regions also match with bright regions in the H\(\alpha\) image (D04). We surmise that the red regions are directly heated by B type stars, and are probably associated with ionized gas, whereas the arcs represented by white color in figure 4b are PDRs surrounding them, which are characterized by strong UIR emissions in the S9W (cf., Onaka 2004). The strength of the incident radiation field at the arcs (b, c, and f) is estimated based on the projected distance from these heating sources as 900, 3000, and 800, respectively, in units of the solar neighborhood value (1.6 \(\times\) \(10^{-6}\) W m\(^{-2}\), Habing 1968). These are comparable with those of typical PDRs (cf., Mizutani et al. 2004).
IRAS observations indicate an increase of the ratio of 25 μm to 12 μm intensities in the vicinity of heating sources for several cases (Boulanger et al. 1988; Ryter et al. 1987). The UIR band emission largely contributes to the IRAS 12 μm band. The variation in the intensity ratio has been attributed to the increasing contribution from thermal emission of large grains rather than the destruction of the UIR band carriers. Recent investigations on the infrared diffuse radiation of our Galaxy and the Large Magellanic Cloud have in fact shown that the variations in the infrared SED of the diffuse emission can reasonably be interpreted in terms of a superposition of the model emissions, in which the contribution from dust grains in radiative equilibrium becomes large in the vicinity of heating sources together with the effect of destruction of the UIR band carriers in strong radiation fields (Sakon et al. 2006; Onaka et al. 2007a). The band profile of the IRC S9W is shifted to shorter wavelengths compared to the IRAS 12 μm band, and thus S9W probes the UIR band emission more sensitively and is less subject to thermal emission in longer wavelengths (Onaka et al. 2007b). Consequently, the effect of thermal emission near the exciting source appears clearly in the color map of S9W/S11/L18W. The red color in figure 4 points to a region strongly heated by heating sources, whereas the white color indicates a region where the UIR band emission is dominant. The observed color variation is well accounted for by the increasing contribution from thermal dust emission. It further indicates that the UIR-band dominating infrared bright regions (white in figure 4b) are always located in the north-east side, suggesting the presence of high-density regions in this side.

To examine the distribution of young stellar object (YSO) candidates in this region, objects with red color in the near-infrared were selected from the 2MASS catalog. The interstellar reddening to the IC 4954/4955 region was estimated to be $E(B-V) = 0.91$ (D04), which corresponds to $(H-K) = 0.18$ (Rieke & Lebofsky 1985). Taking account of the internal extinction, we conservatively set the criteria that $H-K > 0.9$ and $J-H > 0.9$ to select YSO candidates. They are shown by the red circles and other blue 2MASS sources are indicated by the blue circles in figure 4b. Most of them are located in the white color region as well as in between the two nebulae, where the optical image shows few stars (see below). Only a few red objects are present inside the arcs, indicating that YSO candidates are concentrated in dense regions slightly away from those directly heated by B-type stars. Five of the 2MASS red objects are detected in the S11 image (C, F, J, K, and L). All of them show YSO-like SEDs in the near- to mid-infrared (subsection 3.2; cf., Whitney et al. 2003; Reach et al. 2004), supporting the validity of the adopted criteria. There is also one red object in the relatively red color region without any corresponding early-type stars. It may also play a role of an embedded heating source in the region. A summary of the relations among the various extended (a–n) point-like sources is given in table 4.

A comparison of figures 4a and c indicates that the density of stars is low in between IC 4954 and IC 4955 in the optical image, whereas the dust emission is seen in the corresponding region in the WIDE-L (140 μm) image. The size of the region (120′′) is sufficiently larger than the FWHM of the beam size of the WIDE-L band (~58′′; Kawada et al. 2007), and thus the presence of far-infrared emission in between the two nebulae is not spurious. It can be surmised that the region is a dark nebula filled with dust grains. The region around source F in figure 1b also appears dark in the optical image, suggesting that source F is surrounded by a large amount of dust.

The mid-infrared color variation, the location of early-type stars, and the distribution of red objects strongly suggest that YSOs are being born in the region on the north-east side of the arcs. Their formation may be triggered by the existing early-type stars, and star-formation is propagating from south-west to north-east. This picture is revealed by the high spatial resolution (especially in 11 μm) and the multi-band (especially 140 or 160 μm) infrared data of AKARI. Because of the arc-like shape, rather than the cometary shape, it is conjectured that the regions where YSOs are concentrated in IC 4954/4955 are not pre-existing clouds imploded and/or evaporated by the effect of stellar winds, such as in the Elephant Trunk Nebula (Reach et al. 2004), but are rather triggered by the ‘collect and collapse’ type mechanism with stellar winds of the heating stars (Elmegreen 1998). Rather uniformly distributed YSOs may also support this interpretation (e.g., Efremov & Elmegreen 1998).

**Table 4.** Structures and point sources in the mid-infrared of the IC 4954/4955 region.

<table>
<thead>
<tr>
<th>S11</th>
<th>S18W</th>
<th>Comments</th>
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<td>a</td>
<td>F</td>
<td>g</td>
</tr>
<tr>
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<tr>
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<tr>
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The peak positions are matched within the uncertainties.
4.2. Origin of Roslund 4

To investigate the origin of the IC 4954/4955, mid-infrared maps of the surrounding region of about $1^\circ \times 1^\circ$ at 9 and 18 $\mu$m were created from the IRC All-Sky Survey data. The S9W/18W color image is shown in figure 6a with the contours of the 100 $\mu$m data of the IRAS Sky Survey Atlas (ISSA, Wheelock et al. 1994). It indicates that there is a cavity of low mid-infrared emission centered around ($\alpha$, $\delta$) = (20$^h$03$^m$, +29$^\circ$00$''$) and that the IC 4954/4955 region is located on an edge of the cavity.

To examine and confirm the presence of the cavity, H I 21 cm data of the region were obtained from the Canadian Galactic Plane Survey (CGPS) and examined. Figure 7 shows a plot of the intensity vs. velocity of the H I data. It indicates that the H I gas in this region has a velocity range of 0–30 km s$^{-1}$. This is in good agreement of the velocity range of CO emission associated this region of 6–19 km s$^{-1}$ (Leisawitz et al. 1989). The H I intensity integrated over 0–30 km s$^{-1}$ is shown in figure 6b, which clearly supports the presence of a low-density cavity around the center of the map. In figure 6b, also plotted by crosses, are YSO candidates. They were selected from the 2MASS catalog based on the same criteria, $H-K > 0.9$ and $J-H > 0.9$, as in figure 4b. In addition, a condition of 13.5 < $K$ < 15.0 was estimated from the $K$ magnitude of the YSO candidates in figure 4b and applied to exclude foreground and background sources. The symbols $\alpha$, $\beta$, and $\gamma$ indicate the regions where a concentration of YSOs is seen. YSO candidates seem to be located on the edge of the cavity. It is most clearly seen in the eastern edge, which includes the IC 4954/4955 region as well as the regions $\alpha$ and $\beta$; however, only a few YSOs are found at the north and south edges.

The radius of the cavity is estimated to be about 10 pc. The cavity is elongated and partly collapsed. Such structures are commonly seen in galactic bubbles (Churchwell et al. 2006). The cavity of the IC 4954/4955 may have been created by supernovae (SNe) or O-type stars. Progenitor candidates were searched for in the Tycho-2 spectral type catalog (Wright et al. 2003), All-sky compiled catalog (Kharchenko 2001), Mean radial velocities catalog (Barbier-Brossat & Figon 2000), and SNRs catalog; but no progenitors of such a kind were

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Fig. 6. (Left) Color image made from the S9W and L18W All-Sky Survey data of AKARI/IRC around IC 4954/4955. The contours indicate the ISSA 100 $\mu$m intensity. (Right) CGPS H I 21 cm map integrated over the velocity range of 0–30 km s$^{-1}$ (see text). The crosses indicate red sources selected from the 2MASS catalog.

Fig. 7. Intensity vs velocity plot of the H I 21 cm data (CGPS). The solid line indicates at the IC 4954/4955 region, whereas the dashed line corresponds to the center of the cavity (figure 6).

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http://www.ras.ucalgary.ca/CGPS

found. No SNR-like structures were found either in the soft X-ray maps of ROSAT or in the NVSS 1.4 GHz map (Condon et al. 1998), although there seem to be some point-like condensations in this region. A cavity with a size of \( \sim 40 \) pc in IC 1396 is made by a single O6.5 star (Patel et al. 1995). Thus, the O8\( ^{\text{ii}} \) star located south-west of IC 4954/4955 (figure 4b) could be a progenitor because the dense region is spread north-east of the cavity. However the star may be too young if the age of Roslund 4 is 15 Myr and the star-formation was delayed relative to the trigger event because of the internal motions (Elmegreen 1998). Since SNRs disappear in the time scale of \( \sim 1 \) Myr and the age of the cavity must be older than 4 Myr, based on the age of Roslund 4, it is not unexpected that there is no direct sign for the progenitor. The Cepheus bubble (Patel et al. 1998) is also thought to be formed by O-type stars or supernovae, but shows no direct hint of them. The present AKARI observations have revealed another bubble of small scale, which seems to trigger past (4–15 Myr old) star-formation in IC 4954/4955. It also indicates ‘current star-formation’ in the region, which is triggered by stars of the second generation. This trigger seems to be different from the ‘globule-squeezing’ type in the Elephant Trunk Nebula near the Cepheus bubble. The present observations indicate triggered star-formation over the three generations in a different spatial scale in the IC 4954/4955.

5. Summary

With the two scientific instruments (IRC and FIS) on board AKARI we obtained 7 band images of IC 4954/4955 from 7 to 160 \( \mu \)m with higher spatial resolution and higher sensitivities than previous observations. Based on these observations we obtained the following results:

(1) The mid-infrared images at 9, 11, and 18 \( \mu \)m reveal several distinct structures in the region. Particularly, they show three arc-like structures that seem to have been created by stellar winds from the existing B type stars. The difference between the S9W (9 \( \mu \)m) and S1I (11 \( \mu \)m) images is not significant, indicating that the variation in the spectrum of 6–13 \( \mu \)m is not large, and that the contribution of line emission from ionized gas, such as [Ne II] 12.8 \( \mu \)m, is relatively small compared to the UIR band emissions at 6.2, 7.7, and 11.2 \( \mu \)m.

(2) The S9W (9 \( \mu \)m) to L18W (18 \( \mu \)m) images appear to be systematically different from each other. The L18W emission is strong near the exciting stars, whereas the S9W emission is dominant in the surrounding region. The S9W filter probes the UIR band emission more effectively than the IRAS 12 \( \mu \)m because its band profile is shifted to shorter wavelengths. We interpret the systematic mid-infrared color variation in terms of the decreasing contribution of thermal dust emission with the distance from the exciting source. The color variation clearly indicates the location of exciting stars, suggesting that the star-formation in IC 4954/4955 is progressing from south-west to north-east.

(3) Young stellar objects are distinguishable for the first time at 11 \( \mu \)m. They are located in the large S9W to L18W ratio regions, suggesting that current star-formation has been triggered by previous star-formation activities.

(4) The FIS data allow one to correctly estimate the total infrared luminosity from the region, which is about one sixth of the energy emitted from the existing early-type stars. Thus, there is little possibility that embedded luminous stars have escaped detection. It also suggests that the total dust mass of the infrared emission is about 60 \( M_\odot \). The 140 and 160 \( \mu \)m images reveal the presence of a high-density region between IC 4954 and IC 4955, which is also supported by optical images.

(5) The IRC All-Sky Survey data together with the H I 21 cm data further suggest the presence of a bubble-like structure of a degree scale, on whose edge the IC 4954/4955 region is located, indicating triggered star formation over three generations.

The IC 4954/4955 region is not a massive star-formation region, and is currently populated by B type stars. The mass of the infrared emitting material is also not huge. The suggested hole of the interstellar matter is not large, and thus should be created by a less energetic event compared to IC 1396. The present observations suggest that even in such a moderate star-forming region sequential star-formation occurs and is on-going at present. Medium-scale star-formation could be common and should be studied in future investigations.

AKARI continues to provide significant data for the study of interstellar medium and star forming regions owing to its high sensitivity, wide wavelength coverage and wide mapping capability, during the course of its mission.

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